Simulation Study of Fractional Frequency Reuse in WiMAX Networks

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WiMAX is a metropolitan area network (MAN) wireless technology that provides high-quality broadband services to mobile users. For maximum usage of the available spectrum, each cell should operate on the whole available bandwidth. However, this leads to unacceptable interference for cell edge users and reduces the coverage. This paper reports on a study of fractional frequency reuse (FFR) in WiMAX networks, which is a promising approach for reducing interference at the cell edge. Simulation results show that FFR can provide significant coverage gains by reducing the cell edge interference while retaining high utilisation of the spectrum. FFR can therefore be regarded as an essential technique for interference management in WiMAX networks.

1. Introduction

The WiMAX technology is currently viewed as the leading candidate for providing broadband wireless services with very high quality of service (QoS) levels comparable with digital subscriber lines (DSLs). Mobile WiMAX (known as IEEE 802.16e), which is the latest version of the IEEE 802.16 family of standards, allows broadband wireless access even for highly mobile users. The current IEEE 802.16e standard[1) supports downlink data rates of up to 63 Mb/s,[2) while the modified IEEE 802.16m standard under development envisages data rates in excess of 100 Mb/s. One of the innovative adaptations in Mobile WiMAX is the use of orthogonal frequency division multiple access (OFDMA), where different users are multiplexed with time-frequency resource allocations in the same transmission frame. Each user is allocated sub-channels made up of a fixed number of narrowband sub-carriers. These sub-carriers are orthogonal to each other, so there are negligible levels of interference amongst them in a single cell/sector. The main source of interference is the use of the same sub-carriers in the same time slots within nearby cells/sectors. These instances are termed collisions. The 802.16e standard allows the use of the same frequency band in adjacent cells/sectors (known as frequency Reuse 1 or R1 in cellular network planning). While this can improve the overall network throughput, the users near the cell edge will experience unacceptable levels of interference due to the very high level of collisions, resulting in low coverage. The 802.16e standard provides random sub-channelisation schemes,[1) where the users in adjacent cells select sub-carriers according to pseudo-random sequences to minimise the collision probability. However, the full spectrum of sub-carriers gets used up quickly (especially in the downlink), so the benefit of random sub-channelisation is thus lost.

The solution to this interference problem proposed in the standards is fractional frequency reuse (FFR). In FFR, the users at the cell/sector edge operate with a fraction of all sub-channels available while the inner cell users operate with all sub-channels available. The cell edge users usually operate with frequency Reuse 3 (also termed R3), while the inner cell users operate with R1. In frame transmission aspects, the R3 users are grouped into an R3 zone, which is separated in time from the R1 zone. The perceived benefits of FFR lie in the provision of better signal quality to the cell edge users through the physical separation of the interference sources. The improved signal quality is also expected to bring about higher throughput for the cell edge users. However, this comes at the cost of lower spectral resource allocation, so it is important to analyse whether the benefits outweigh the costs.

In this paper, we discuss the performance of FFR based on an extensive analysis using system level simulations. One of the key factors deciding FFR performance is the criterion used to allocate users to the R1 and R3 zones. This aspect is discussed in Section 2, which explains the various parameters that can be used to carry out dynamic zone allocation. Section 3 describes the configuration of the system level simulator (SLS) used for the FFR analysis. Results are presented and discussed in Section 4. The main conclusions from this study are presented in Section 5.

2. Implementation of FFR concept

The FFR concept can be theoretically explained as excluding the cell edge users from the frequency R1 operation and assigning them only a sub-set of the available sub-channels. This is illustrated in **Figure 1** (taken from Reference 2), where F_A, F_B, and F_C are different sets of sub-channels in the same frequency channel. In this configuration, the full load frequency R1 operation is maintained for central users to maximise spectral efficiency, while FFR is used for cell edge users by employing R3 operation. Also shown is the transmission frame structure with time and frequency resource allocations for the R1 and R3 zones. The frame control header/media access protocol (FCH/MAP) part provides sub-channel allocation information, which allows the users to locate their resource block within the frame. Additionally, the FCH/MAP part carries other signalling such as the zone switch information elements, which indicate switching points between the R1 and R3

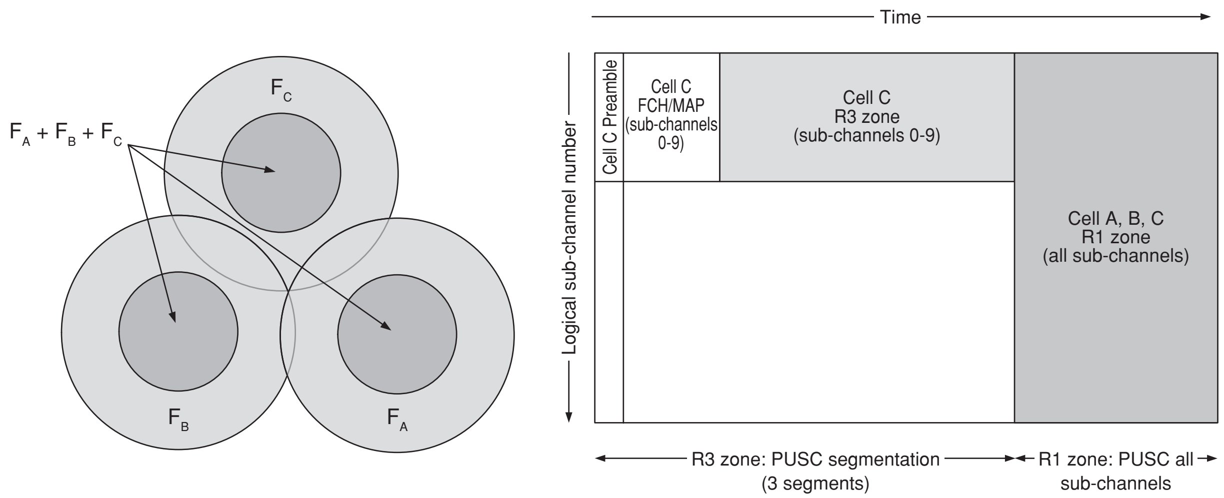

Figure 1
Implementation of FFR in cell planning[2] and DL frame transmission.

zones.

The initial release of the Mobile WiMAX certification profile includes a time division duplexing (TDD) mode.[2] In TDD, the uplink and downlink transmissions are carried out consecutively over time, separated by guard gaps. Thus, the transmission frame is divided into two sub-frames. Furthermore, there are different zones for frequency R1 and R3 operation (known as the R1 and R3 zones) within the sub-frames. These have common boundaries for all the cells/sectors operated in the network, so there will be no inter-zone interference between R1 and R3. One advanced concept is to dynamically vary this zone boundary (across the network) depending on user behaviour and cell loading. However, we did not consider this in the study reported here, where the zone sizes were kept fixed throughout the simulations.

One of the key aspects of user assignment into the R1 and R3 zones is the dynamic nature of the FFR zone assignment, which must be in line with the users' signal quality and positioning variations. The base station (BS) must obtain regular feedback from the user (or mobile station [MS]) and the BS must decide whether to allocate the MS to R1 or R3. With faster user movement, these updates need to be more frequent, requiring more overhead. There is always a trade-off between the accuracy of zone assignment and the overhead required for feedback and signalling.

The FFR zone assignment decision at the BS for a particular user may be based on several parameters. These parameters need to be determined from feedback signals from MS to BS, as supported in the 802.16e standard.[1]

As described above, FFR is implemented for the benefit of the cell edge users. Hence, an obvious zone assignment parameter to consider is the range (distance) from the BS to a given MS. This scheme is simple to implement and the BS can ensure full utilisation of the R1 and R3 zones by fine tuning the distance threshold. However, a major drawback of this distance-based assignment is that the short-term (or even medium-term) signal quality does not necessarily correlate with the distance from the BS because radio signal variations can be highly localised as a result of effects known as fast fading and shadowing. In this respect, a better parameter for zone assignment is the received signal quality of the data channels at the MS. In this study, we investigated a proprietary FFR algorithm, which requires minimal feedback from the MS to the BS.

3. Simulation configuration and description

Simulations of the downlink of a Mobile WiMAX system with FFR were carried out using a proprietary WiMAX system-level simulator (SLS). The SLS models a multi-cell Mobile WiMAX network with a wrap-around cell layout, which ensures that all cells experience the same interference characteristics. The following main models are used by the SLS: user movement, handover between cells/sectors, path loss, shadowing, fast fading, and wrap-around. The simulation parameters are summarised in **Table 1**. In all simulations, error free feedback from the MS to the BS was assumed.

4. Results and analysis

The performance of FFR in a Mobile WiMAX system was evaluated with the WiMAX SLS using the parameters specified in Section 3. Results obtained for the two non-FFR reference cases of pure Reuse 1 and Reuse 3 are also provided.

The geographical distribution of the probability of assignment into the FFR R1 zone is shown in **Figure 2**. As expected, the FFR method placed users into the R1 zone, which were located close to the cell centre and within the main radiation lobes of the BS antennas. Thus, the FFR method assigned users close to the base station with a high probability into the R1 zone, while cell edge users were assigned with a high probability into the R3 zone.

Next, the effect of FFR on the average sector throughputs was investigated. The average sector throughput results in **Figure 3** show that FFR achieved an 18% throughput gain compared with pure Reuse 3; however, there was a 13% throughput reduction compared with pure Reuse 1.

Compared with a pure Reuse 3 system, FFR placed users with good signal quality into the R1 zone, which resulted in a throughput increase. However, compared with a Reuse 1 system, FFR was found to achieve lower throughputs. This can be explained as follows: Although the signal

Table 1
Simulation parameters.

Parameter	Setting
Site-to-site distance	1.6 km
Carrier frequency	2.5 GHz
Operating bandwidth	10 MHz in TDD mode
Path loss model	COST 231 Hata urban macrocell model
Shadowing	8-dB standard deviation with log-normal distribution; de-correlation distance: 72.5 m
Users per sector	60
User speeds and multipath model	120 km/h; VA120
Number of BS antennas per sector	2 Tx antennas
Number of MS antennas	2 Rx antennas
Antenna height at BS	32 m
Antenna height at MS	1.5 m
MIMO mode	Matrix A (STC)
Traffic type	Full buffer
Scheduler	Proportionally fair (PF)

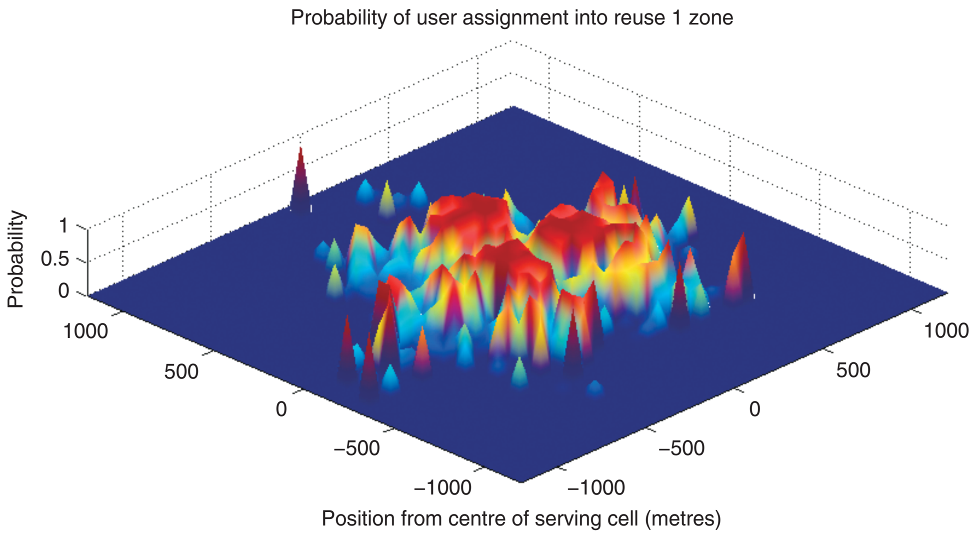

Figure 2
Probability of assignment into FFR R1 zone.

quality, expressed by the carrier to interference plus noise ratio (CINR) improves by about 10 dB when a cell edge user moves from the R1 zone to the R3 zone and more efficient transmission can consequently be achieved (i.e., a higher modulation and coding scheme can be used), the availability of only one third of the bandwidth generally results in lower throughput in the R3 zone compared with the R1 zone at the cell edge. The only exception to this is when a cell edge user cannot be served in the R1 zone because the signal quality is too poor while the R3 zone allows the user to be served. This finding is also supported by an FFR throughput analysis[3] performed in the context of next-generation (4G) mobile networks.

Another aspect when optimising FFR algorithms is the radio resource utilisation in the R1 and R3 zones, which is defined as the ratio of used slots to the total number of available slots in the DL sub-frame. As shown in **Table 2**, both the pure Reuse 1 and Reuse 3 systems fully utilise the resources. However, the FFR method underutilises the R1 zone. Therefore, with an additional optimisation of the FFR zone utilisation (which is not considered in this work), better resource utilisation could be achieved, which might result in improved throughput.

So far, we have seen that a pure Reuse 1 system obtains the highest average sector throughput. However, another important issue when evaluating a wireless system is the coverage, which describes the percentage of users that can be served, i.e., experience good enough signal quality. Therefore, in an optimised system the coverage should be as high as possible. The cumulative distribution function (CDF) of the preamble CINR is illustrated in **Figure 4** and **5** to show the coverage performance of FFR in two distance ranges from the BS: 100–300 m and 800–1000 m. Assuming that the minimum CINR required for scheduling is −2.6 dB, it can be observed in Figure 4 that with a pure Reuse 1 system, about 74% of users can be served close to the BS. However, with FFR this increases to 96% of users. Figure 5 shows that at the cell edge with a pure Reuse 1 system, only 25% of users can be served, whereas with FFR, 76% of users can be served. Furthermore, FFR provides a similar preamble CINR to a pure Reuse 3 system at the cell edge. These results demonstrate

Table 2
Radio resource utilisation.

Setup	R1 zone utilisation (%)	R3 zone utilisation (%)
Reuse 1	100	N/A
FFR	68	100
Reuse 3	N/A	100

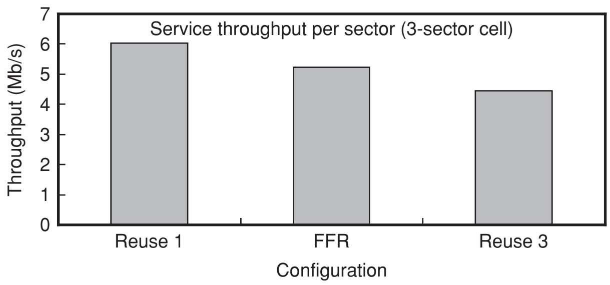

Figure 3
Average sector throughput for Reuse 1, FFR and Reuse 3.

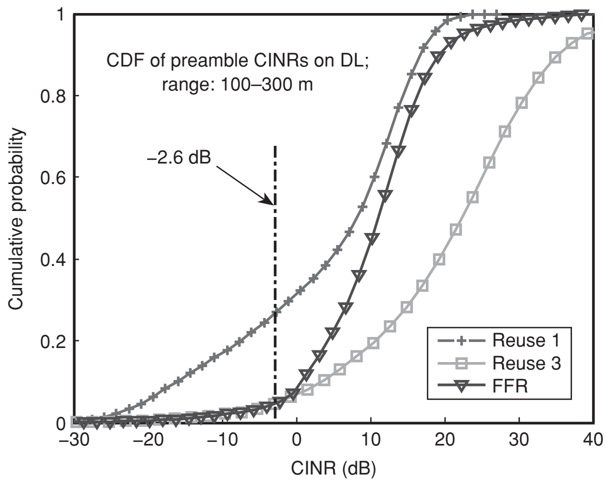

Figure 4
Preamble CINR for Reuse 1, Reuse 3, and FFR within 100–300 m from BS.

that FFR can significantly improve the coverage compared with a Reuse 1 system. It can be concluded that FFR is an essential technique for improving the signal quality for cell edge users because it provides improved coverage and therefore allows more users to be served.

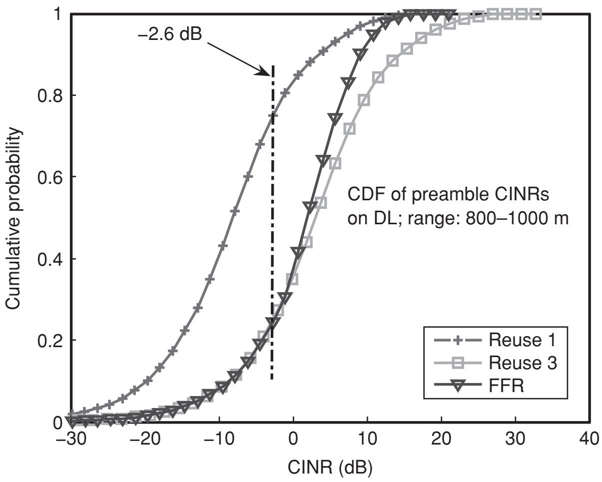

Figure 5
Preamble CINR for Reuse 1, Reuse 3, and FFR within 800–1000 m from BS.

5. Conclusions

This paper reported on our study of an FFR interference mitigation technique in a Mobile WiMAX system through extensive system-level simulations of an FFR algorithm. The key findings are that FFR provides considerably higher coverage than a Reuse 1 system, with the FFR coverage being comparable to that of a Reuse 3 system at the cell edge. Additionally, FFR obtained a significant improvement in sector throughput compared with a Reuse 3 system. However, it did not provide better sector throughput than a Reuse 1 system. It can be concluded that FFR is an essential technique for combating interference at the cell edge in Mobile WiMAX networks.

References

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2) Mobile WiMAX Part I — A Technical Overview and Performance Evaluation. WiMAX Forum document, Aug. 2006.
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Dr. Sarperi received the Ph.D. degree from the University of Liverpool, UK, in 2007 for work on blind and semi-blind receivers for wireless MIMO communication systems. Before that he worked for several years in the telecommunications industry as a hardware and systems design engineer in Switzerland. He joined Fujitsu Laboratories of Europe Ltd., in 2007 as a research engineer, where he is engaged in research on WiMAX wireless networks.

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Mr. Vadgama graduated from the University of Surrey in 1984. Subsequently, he joined Philips Research Laboratories (UK), where his work included the development of advanced mobile communication systems, UMTS, and linearisation of RF power amplifiers. In 1991, he joined Fujitsu (UK), where he was initially engaged in the development of GSM terminals and subsequently in R&D of advanced technologies for IMT2000 base stations. He chaired the Industrial Steering Committee of the Personal Distributed Environments (PDE) research group in the Core 3 research programme of the Mobile Virtual Centre of Excellence in the UK from 2003 to 2005. He is currently Manager of the Wireless Technology Group and Assistant Division Manager for the Network Systems Research Division at Fujitsu Laboratories of Europe Ltd., and is studying the long-term evolution of 3G, WiMAX, the future 4G, and ad-hoc wireless access technologies.